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Energy and Carbon Audit of an Offshore Wave Energy Converter

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ABSTRACT

The world's first commercial wave farm will feature the 'Pelamis' wave energy converter developed by Ocean Power Delivery. With potential for the manufacture of significant numbers of such devices there is a need to assess their environmental impact and, in particular, their life cycle energy and carbon dioxide (CO_2) performance.

This paper presents an analysis of the life cycle energy use and CO_2 emissions associated with the first generation of Pelamis converters. With relatively conservative assumptions, the study shows that at 293 kJ/kWh and 22.8 gCO_2/kWh the respective energy and carbon intensities are comparable with large wind turbines and very low relative to fossil-fuelled generation. The energy payback period is approximately 20 months and the CO_2 payback is around 13 months.

Material use is identified as the primary contributor to the embodied energy and carbon with shipping (including maintenance) accounting for 42%. Improving the Pelamis' environmental performance could be achieved by increasing structural efficiency, partial replacement of the steel structure with alternative materials, particularly concrete, and the use of fuel-efficient shipping.

Keywords: Carbon dioxide, energy intensity, life cycle analysis, wave energy.

1 INTRODUCTION

Concerns over climate change are driving the transition to a low carbon economy. Renewable energy is expected to play a key role in this, and the Government of the United Kingdom (UK) have implemented the Renewables Obligation (RO) which requires electricity generators to supply 10% of electricity from renewable sources by 2010, with an aspiration of 20% by 2020. The UK has very significant marine energy resources which are believed to have the potential to supply around 20% of electricity demand [1]. The most favourable sites for wave energy tend to be located off the Scottish north and west coasts where mean wave power is in excess of 50 kW/metre of wave front.

One of the wave energy converters (WECs) designed to harness this resource has been developed by Edinburgh-based Ocean Power Delivery Ltd (OPD). Their Pelamis device is an offshore, semi-submerged WEC and is being deployed in Portugal in the world's first commercial wave farm. Successful deployment of the device could lead to development of a programme of wave farms involving manufacture of a large number of Pelamis devices. As such, it is important that the environmental impact of the Pelamis is evaluated and one of the key aspects is its life cycle energy and carbon dioxide (CO_2) performance.

The only existing life cycle studies of marine energy converters have been first order estimates of carbon and energy intensity based on the mass of steel within the structure of the device. Banerjee *et al.* [2] estimate the carbon intensity of the Pelamis device to be just under 40 gCO_2/kWh. The Carbon Trust [1] provide a similar first-order estimate for an unnamed WEC indicating carbon intensity of between 25 and 50 gCO_2/kWh and carbon payback in the region of 14 to 21 months.

In contrast, this paper sets out a detailed life cycle analysis of the Pelamis device which is believed to be the first in-depth assessment published. It evaluates the energy consumption and CO_2 production involved in each stage of its life cycle from 'cradle to grave' which allow derivation of the energy and CO_2 payback times and comparison with other electricity generating sources.

The paper is set out as follows: Section 2 briefly introduces the concept of life cycle analysis, outlines the features of the Pelamis converter and sets out the scope of the study. Section 3 provides a detailed analysis of the embodied energy and CO_2 with Section 4 setting the findings in context.

2 Life Cycle Assessment of Wave Energy Converters

2.1 Life cycle assessment

Life cycle assessment (LCA) is a methodology designed to account for the environmental impacts of products of services over their entire life cycle. Such 'cradle to grave' analyses quantitatively account for all the energy, materials, emissions and waste products associated with everything from the extraction of raw materials to disposal at the end of a product's serviceable life. An indication of the maturity of this methodology is that the ISO 14040 series [3] of international standards governs their execution. LCAs have been applied to a wide variety of energy technologies including nuclear, wind and coal [4]-[11] as well as electrical networks.

Each stage of the product life cycle is evaluated in detail (Figure 1). Data on the energy and emissions from each stage is then gathered and, where not available, justifiable assumptions made. This results in a comprehensive analysis highlighting the components, materials or stages of the life cycle that have the largest environmental effects. This information can then be used for decision making based on environmental impact, for marketing product environmental credentials to potential customers and in identifying possible improvements.

LCA is not an all-inclusive definition of product sustainability as there are influencing factors not covered by the methodology, e.g., visual impact, which must be analysed by different means, such as Environmental Impact Assessment. There are limitations to LCA including assumptions regarding system boundaries and data sources which may introduce subjectivity [12]. Additionally, the use of confidential data poses particular problems for the verification of LCA [13]. Further reading on LCA can be found in [14]-[15].

2.2 Pelamis Wave Energy Converter

The Pelamis wave energy converter is developed and manufactured by Ocean Power Delivery Ltd., an Edinburgh-based company spun-out from the Wave Power Group at the University of Edinburgh in 1998 [16]. The Pelamis is a semi-submerged snake-like device (the name means 'sea-snake' in Latin) consisting of articulated cylindrical sections linked by hinged joints (Figure 2). The first versions are 120 m long, 3.5 m in diameter and rated at 750 kW. The compliant moorings allow Pelamis to face into the oncoming waves with the joints flexing vertically and horizontally (i.e., heave and sway) as waves run down the length of the device (Figure 3). The hydraulic power take-off (PTO) uses the motion of the joints as resisted by hydraulic rams to pump high-pressure oil into banks of accumulators. The accumulators are drained at a constant rate through hydraulic motors, which in turn drive induction generators. The resistance of the hydraulic rams can be manipulated to give a resonant response in small sea states, maximising power capture, as well as de-tuning to potentially damaging storm waves. A full description of the PTO system is given in [17].

The Pelamis evolved through a rigorous programme of experimental scale model testing, culminating in a full-scale prototype being installed at the European Marine Energy Test Centre in Orkney and the first offshore wave energy being supplied to the UK grid in August 2004. The world's first commercial wave farm will enter service in summer 2007 with three 750 kW Pelamis production devices forming a 2.25 MW wave farm in Peniche, Portugal. With grant funding from the Scottish Executive, Scottish Power will build the UK's first wave farm in Orkney featuring four Pelamis units. The 3MW farm will cost £10m and will be commissioned in summer 2008

The Pelamis is designed for offshore sites with water depths of 50 to 100 m. OPD estimate that Pelamis production machines will produce 2.7 GWh per year for typical sites off the north west coast of Scotland where mean wave power levels are approximately 55 kW/m. OPD expect that improvements made to the control system and mooring will offer the potential to substantially increase power capture over time, possibly by as much as 50%. For the purposes of this study it has been assumed that Pelamis machines would capture 10% more energy than initially estimated, raising production to an average of 2.97 GWh/year over the machine's design life [18].

2.3 Study scope and boundary

The definition of the system boundary is important to inform as to what is, and what is not, included in the analysis. This study achieves a 'cradle to grave' boundary by considering all energy input and carbon emissions from the extraction of the raw materials used in manufacture from their natural state to the complete disposal of the machine at its end-of-life (Figure 4). Physically, the system boundary encompasses the moorings and umbilical sub-sea transmission cable but all downstream elements of the electricity transmission system are outside the scope of the LCA.

This study presents a generic case for the production of a single Pelamis based on materials used in the first production machines. As such, all values for embodied energy and carbon are for this single device. Although updated versions of the Pelamis are expected to possess a superior power to weight ratio, a fixed scenario of manufacture, assembly and deployment was defined for this study.

It is assumed that all major components and sub-components are manufactured in the UK and subject to UK energy statistics and transport distances. The typical wave farm in which a device will be deployed is assumed to lie within a 200-mile radius of a commercial port (implying vessel travel times of 24 hrs at 6 knots). In line with DEFRA guidelines [19], it is assumed that the electricity consumed throughout the life cycle comes from the UK grid and has a CO_2 intensity of 0.43 $kgCO_2/kWh$. The energy and emissions associated with the manufacture of capital plant and machinery used during the Pelamis life cycle have been excluded but the typically much more significant operational impacts (e.g., electricity consumption) are included.

3 LIFE CYCLE INVENTORY ANALYSIS

3.1 Procedure

Previous studies have shown that for wind turbines, the most significant environmental impact arises during the manufacture of the turbine rather than through operation and maintenance [7]-[9]. The primary focus of this study was to collect the most accurate data available for the manufacturing stage of the life cycle. Where complete data for a component has been difficult to obtain, alternative sources have been used including previous LCA studies.

The vast majority of the Pelamis device has been analysed directly in terms of its materials, processing and mass. However, with the electrical and electronic systems comprising large numbers of smaller components, it was necessary to use capital cost methodologies to estimate energy and CO_2 emissions. Given the expected modest contribution of these systems to overall embodied energy and carbon, this approach was appropriate but precluded the presentation of a complete materials and mass classification for the device; this is clearly an area for further work.

3.2 *Raw materials*

The preference in this study has been for data derived from OPD's own records and, in particular, that related to the Pelamis model currently in production although this was not necessarily the most recent. Data from UK sources was favoured but, where unavailable, European average data has been used. Data for material embodied energy and carbon is taken throughout this study from the Inventory of Carbon and Energy (ICE) [20], a database compiled by the University of Bath. The dataset offers a 'cradle-to-gate' assessment covering exploration and extraction of the raw and feedstock materials to the production of the processed material ready for collection at the factory gate. Its well-documented methodology is designed to ensure consistency and remove ambiguity through rigorous survey of secondary sources, and is derived, where possible, from UK sources. It is therefore suited to UK-based applications. The data for key materials is given in Table 1. Aspects not covered by the ICE (e.g., manufacturing processes, exotic materials, etc.) have been sourced from the literature: technical journals, conference papers and previous LCA studies, preferably accredited to ISO 14040.

Material	Embodied Energy (MJ/kg)	Embodied CO_2 ($kgCO_2/kg$)
Aluminium (range: rolled – cast)	150.2–167.5	8.35–9.21
Copper	55	4.38
Nylon 6	120.5	5.5
Paint	80	6.1
Polyurethane	72.1	3
PVC Pipe	67.5	2.5
Sand	0.1	0.005
Stainless Steel	51.5	6.15
Steel (range: engineering – plate)	11.7–45.4	0.68–3.19

Table 1: Energy consumption and CO_2 emissions for materials used in Pelamis [20]

3.3 *Manufacture*

This stage of the life cycle includes everything from the extraction of raw materials, through their processing and manufacture into sub-components and ends with the production of the major components of the Pelamis WEC ready for final assembly. The cost of manufacturing is dominated by the structure (66%) with the hydraulic systems (23%) and electrical and electronic systems having more modest shares. The large weighting of the structural elements reflects the mass distribution and it was expected that this section would have the greatest impact on the total embodied energy and carbon.

3.3.1 Structure

Figure 5 indicates the structure of the Pelamis which comprises four cylindrical sections, the Power Conversion Modules (PCM) as well as the Yoke that connects the Nose Tube to the moorings.

When considering the manufacture of each of these elements, the LCA must consider the energy and CO_2 resulting from further processing of the stock materials. These processes include casting, flame cutting, machining, welding, blasting and painting. The relevant conversion factors applied for these processes are summarised in Table 2 and explained briefly below:

- Sand-cast steel components were taken as 'general steel' and with the energy consumption and CO_2 emissions based on electricity [21].
- Standard steel plate is profiled using oxy-acetylene flame cutting [22].
- With no specific LCA data available for milling, grinding or drilling processes, estimates were based on the energy required to remove a unit volume of material [23].
- The structure is fabricated using electrically-welded steel plate and, while the figures used [22] relate to thinner plate used in ship building, the underestimate in energy and carbon terms is likely to be small.
- Blasting prepares the structure for the protective coating. In the absence of data on shot or grit blasting, data for sand [20] was used assuming that 10 m^3 of sand is required to blast 1 m^2 [22]. A lack of data prevented air compressor operation from being accounted for and although compressors suffer from low efficiencies this was anticipated to be a relatively minor omission.
- A specialised 'glass flake' paint coating is used to minimise marine corrosion and as no suitable LCA was available a generous but reasonable 500 µm thick coating was assumed. With coverage of 0.399 kg/m^2 based on other glass flake paint [24], appropriate energy and carbon factors were derived from [20].

Process	Energy Input	CO_2 Emissions
Sand Casting [21]	9.8 MJ/kg	1.172 $kgCO_2/kg$
Flame Cutting [22]	8.5 MJ/m^2	1.015 $kgCO_2/kg$
Machining [23]		
Aluminium	1.1 kJ/cm^3	0.1 gCO_2/cm^3
Steel	9.3 kJ/cm^3	1.1 gCO_2/cm^3
Stainless Steel	5.2 kJ/cm^3	0.6 gCO_2/cm^3
Welding [22]	15.1 MJ/m	1.804 $kgCO_2/m$
Sandblasting [20] [22]	1.0 MJ/m^2	0.053 $kgCO_2/m^2$
Painting [20] [24]	31.9 MJ/m^2	2.434 $kgCO_2/m^2$

Table 2 – Conversion factors for post-processing operations

Tube Sections

The tube sections of the Pelamis account for most of its mass and the hydrodynamics dictate that the tube length increases from fore to aft (i.e., nose to tail). As currently configured, the Pelamis consists of four tube sections: the Nose Tube, two Mid tubes and the End Tube, as shown in Figure 5. The front section of the Nose Tube is tapered to allow the machine to cut through the waves. It also connects to the Yoke as well as housing the transformer. The rear section of the Nose Tube is an 'end cap' that connects the tube sections and Power Conversion Modules. The two central tubes have end caps on either end of the cylindrical 'shell filler' section while the End Tube has a single end cap.

Manufacture of the tube sections is split between the shell filler sections and the relatively more complex nose cone, Yoke-connection body, and end caps. The manufacture of the shell filler sections is a largely automated process with standard steel plates cut and rolled into tubular sections which are then welded together. The more complex Yoke connection body and end caps also have tubular steel shells that are fabricated as above but require manual welding of their complex internal structures. Each end cap includes four castings: two bearing sockets and two ram sockets.

The data for the tube sections was derived from fabrication drawings as a high level of detail was required to accurately determine the mass and material classification of each part along with the post-processing operations detailed earlier. Details of the requisite (sand) ballast were also required.

Power Conversion Modules

The three power conversion modules (PCMs) in the Pelamis sit between the tube sections and house the hydraulic PTO, generators and the control equipment. The manufacture of the PCMs is broadly similar to the more complex elements of the tube sections. Here all PCMs are treated as identical. The procedure for analysis for the PCMs was the same as that of the tube sections with the PCMs painted inside and out.

Yoke

The Yoke, which is fabricated primarily from steel pipe, is the Y-shaped element that connects Pelamis to its mooring and cabling system and is attached to the nose tube. The mooring and cabling system are connected to the Yoke via a quick release mechanism facilitating straightforward latching/re-latching operations for onshore maintenance.

Summary

The total mass of the structure is 859 tonnes. Figure 6 shows the mass of each section, split into the structural materials (largely steel) and ballast (sand).

The total energy required for manufacture is 17214 GJ and carbon emissions are 1251 tCO_2. Figure 7 shows the respective distribution of embodied energy and carbon between the elements. There is a good relationship between the size of the section and the embodied energy/carbon. This can be seen by comparing Figures 6 and 7 for the structural materials only as the relatively small embodied energy and carbon of the sand used for the ballast has little impact. This relationship is intuitive: larger fabrications require both more stock material and more post-processing. It is important, however, that the relative impact of these two aspects be examined.

The contribution of these factors to total embodied energy is shown in Figure 8 (the breakdown in carbon terms is almost identical) and shows that only casting and painting add any notable amount to the embodied energy. The minimal contributions from post-processing justified a focus on material usage as well as highlighting the limited gains (at this stage) from effort in generating more accurate conversion factors.

3.3.2 Hydraulic systems

The Pelamis' hydraulic systems are almost entirely contained within the three PCMs, each consisting of two pairs of hydraulic rams (one each for the heave and sway axes). As no fully detailed breakdown of the hydraulic system could be made available, the data gathering was limited to the mass and materials of the major components [18]. However, as Section 3.3.1 identified, this was acceptable and is likely to have minimal impact on the overall outcome. The major components of the Pelamis' hydraulic systems have a total mass of approximately 28 t, the majority of which is steel. The resulting embodied energy and carbon values are 670 GJ and 79 tCO_2 respectively.

3.3.3 Electrical & Electronic Systems

The electrical and electronics systems in the Pelamis comprise instrumentation and control as well as internal cabling and transmission. The parts list for these systems runs to over 500 separate elements making classification of these on a mass and materials basis unfeasible due to time and resource constraints, particularly considering the complex sub-assemblies of electrical and electronic components. However, an alternative methodology was employed using derived relationships between capital cost and embodied energy/carbon for each component.

This method is derived from the analysis presented by Takayoshi *et al.* [25] for relating the cost of Japanese electronic components to their energy and carbon content. In a similar manner to Rankine *et al.* [9] the 1998 costs in Yen were converted into Sterling and adjusted for inflation. The resulting factors are presented in Table 3.

Description	Energy Conversion (MJ/£)	Carbon Conversion ($kgCO_2$/£)
Semiconductor devices	4.682	0.226
Liquid crystal display devices	4.211	0.196
Cathode Ray Tubes	7.034	0.466
Passive components	8.781	0.423
Connecting components	2.352	0.103
Transducers	4.435	0.203
Printed circuit boards	11.379	0.479

Table 3 – Capital cost to energy/carbon conversion factors for electronics

For non-electronic components, the methodology was based around classifying components by the manufacturing sector in which they were produced. The Digest of UK Engineering Turnover and Orders [26] provides data on the turnover of a number of UK manufacturing sectors (e.g., 'Manufacture of bearings, gears, gearing and driving elements'). The energy consumption and mix of each corresponding sector was then extracted from the Digest of United Kingdom Energy Statistics [27]. Combining these two sets of information provided an approximation of the energy and carbon content of each component based on its capital cost and manufacturing sector:

$$\text{Component energy or } CO_2 = \text{Component cost} \times \frac{\text{Sector energy use or } CO_2}{\text{Turnover of sector}} \quad (1)$$

The capital cost conversion methodologies indicate that manufacture of the Pelamis' electrical and electronic systems results in 466 GJ of embodied energy and 29 tCO_2 of embodied carbon. The methodologies employed in this section are not as accurate as a full mass and material classification and the conversion factors are indicative only. However, the approach is justified on the grounds that it allows inclusion of a large number of components that would otherwise have to be ignored. Since the total embodied energy and carbon for these components is estimated as less than 3% of that of the structure, any inaccuracy will have minimal impact.

3.3.4 Moorings

The mooring system for the Pelamis is designed to be 'compliant' to restrain the machine in position while allowing rotation to face incident waves for optimum power capture. This is achieved by using a 'bird's foot' arrangement of anchored chain and synthetic lines which connect to a quick-release tethering system to provide rapid attachment/detachment of the machine to its moorings. The analysis of the moorings system was based on assessment of material type and mass using data from OPD [18] and the ICE data [20]. The Pelamis' mainly steel mooring system has a total mass of 152 t and its embodied energy and carbon values are 3729 GJ and 432 tCO_2, respectively.

3.4 Assembly and Installation

OPD provided information on the assembly processes and sea vessel operations associated with assembly and installation of the Pelamis. These include installation of the moorings and power cabling, sea trials, initial tow to site and latching to the moorings. Three types of vessel are used: tugs, barges as well as 'multicats', multi-purpose vessels with lifting capabilities. For each installation activity the transport of the part from the supplier was defined, in terms of distance and medium, as was the plant usage. The energy and CO_2 associated with these were based on DEFRA's vehicle emissions guidelines [19] or actual fuel consumption in the case of shipping. With no LCA data available for lifting and handling plant, a range of vehicles with similar engine sizes and weight capacities were identified, e.g., fork-lift trucks equivalent to commercial vans and 100 t overhead cranes deemed equivalent to a fully-laden articulated lorry. The embodied energy and carbon values associated with the Assembly and Installation phase are 2249 GJ and 174 tCO_2 respectively.

3.5 Operations and Maintenance

Maintenance operations (O&M) will be required annually and will feature sea vessels for most activities. OPD anticipate that two unlatching/relatching operations (i.e., detachment from mooring, tow ashore and re-deployment) as well as six inspections of the mooring using remotely-operated vehicles (ROVs) will be required annually. With no Pelamis devices currently in operation, these quantities are necessarily estimated, and may be subject to change once operational experience has been gained. However, it is understood that these are conservative estimates in line with the key aim of confirming and ensuring survivability. The same data and calculations apply to O&M as to assembly and installation. Throughout the 20 year design life, O&M on the Pelamis will involve a total of 40 unlatching/relatching operations and 120 ROV inspections. This results in embodied energy and carbon values of 4712 GJ and 366 tCO_2, respectively.

3.6 Decommissioning and Disposal

As no Pelamis has yet been installed, the decommissioning process was estimated in terms of vessel usage to cover the final unlatching and tow to disposal yard and the recovery of all moorings hardware.

A key aspect of the disposal of the device relates to the potential to recycle certain components and, in doing so, avoid the energy and emissions that would otherwise occur with extraction of primary materials. The relative savings in energy and emissions is allowed as a *credit* to the life cycle and reduces overall energy and CO_2 intensities. Allowable under ISO 14040 [3], a series of methodologies have been developed to account for the recycling of steel [28], aluminium [29] and other metals. The key factor in determining the level of credit is the rate of recycling [27].

Here a recycling rate was assumed for the Pelamis based on two detailed assessments of large wind turbines produced by Vestas. The first [7] applied a conservative 90% recycling scenario for steel to account for uncertainty. The later study [8] assumed 100% recycling of steel. Given the level of uncertainty here, a 90% recycling scenario was assumed with the data based on the same ICE values [20] applied to the manufacturing stage.

A total of 563 t of steel is to be recycled at the end of the Pelamis life cycle, resulting in a credit to total energy and carbon LCI values of 11663 GJ and 978 tCO_2, respectively. With the recycling rate able to materially affect the overall life cycle analysis, its effect is investigated in the sensitivity analysis in Section 4.4.

3.7 Summary of Results

Across the entire life cycle of the Pelamis the net embodied energy input was 17417 GJ with the total CO_2 emissions at 1356 tCO_2. Figure 9 shows the embodied energy and CO_2 associated with each of the Pelamis' life cycle stages, respectively. It is clear that manufacture, specifically of the structure, has the greatest impact; also clearly illustrated are the relatively small impacts associated with the manufacture of the electrical and hydraulics systems, the greatest areas of uncertainty. Additionally, the credit afforded by recycling is shown to be a significant factor in mitigating the overall impact of the system. As such, it must be stressed that, in line with similar LCA studies, the results of this assessment are subject to a high level of recycling being achieved at the end-of-life.

While Figure 9 indicated the life cycle impacts, these can be further broken down on a functional basis:

- Embodied energy and carbon of the stock materials,
- Manufacturing operations applied to the stock materials,
- Shipping: all sea vessel operations,
- Transport: all transit of goods not covered by shipping,
- Plant Operations using plant in the assembly and installation phase.

As Figure 10 shows for the CO_2 analysis, the primary contributors to the overall impact of the life cycle of the Pelamis are the production of stock materials for manufacture and shipping operations. Materials contribute 53% to the total embodied CO_2, while shipping contributes 42%; their impact on embodied energy almost identical. This reinforces the need to focus on these areas and suggests that the greatest improvements to the environmental impact of the Pelamis could be made by addressing these two factors.

4 INTERPRETATION AND DISCUSSION

4.1 Energy and Carbon Intensity

To allow comparisons to be made between generating electricity using Pelamis and using other technologies, the energy and CO_2 intensities, i.e., per unit of production, were calculated. This was done by dividing the overall embodied energy and CO_2 emissions by the total production of Pelamis over its lifetime.

At an annual output of 2.97 GWh, the 20-year lifetime production of the Pelamis is 59.4 GWh. With embodied energy of 17417 GJ, the energy intensity of the Pelamis is 293.2 kJ/kWh. With embodied CO_2 of 1356 tCO_2 the carbon intensity is 22.8 gCO_2/kWh; this is lower than those suggested in [1] and [2], despite consideration of the entire life cycle. A discussion on how these values relate to other electrical generation technologies follows in Section 4.2.

The performance of the device can also be measured by payback periods which indicates how quickly embodied energy and CO_2 are 'recovered' by the carbon-free energy produced by Pelamis. The energy payback period is ascertained by dividing the total lifetime energy input by the annual energy production:

$$\text{Energy Payback} = \frac{\text{Lifecycle embodied energy}}{\text{Annual energy production}} \tag{2}$$

The energy payback is therefore approximately 20 months. Similarly, the carbon payback is the ratio of total embodied carbon and the annual carbon avoided by the use of the system:

$$\text{CO}_2 \text{ Payback} = \frac{\text{Lifecycle embodied CO}_2}{\text{Annual CO}_2 \text{ avoided}} \tag{3}$$

The CO_2 avoided by the Pelamis will depend on what generation is displaced and is time and location dependent. Despite this, it is accepted practice to use the average carbon intensity of grid electricity for the calculation of avoided CO_2 with the figure of 0.43 $kgCO_2$/kWh advised by DEFRA [19] and used in the first-order studies [1]-[2]. Use of this value suggests generation from the Pelamis avoids 1277 tCO_2 per year indicating a carbon payback period of around 13 months.

4.2 Comparison with other generation technologies

Figure 11 shows the carbon intensity of a range of electrical generation technologies. It is clear from this figure that the Pelamis shows a significant improvement in comparison to fossil fuel electrical generation. Relative to other renewable technologies, carbon intensity is significantly lower than that of solar photovoltaic cells and slightly higher than that of wind and hydro power. It should be noted that direct comparison with values from other LCA studies can be problematic, as the assumptions may be different along with issues regarding compliance with the ISO standards. Overall, given that the Pelamis is still in a relatively early stage of development and designed for 'survivability before power capture efficiency' [16], the results of this work should not be taken as anything other than encouraging.

4.3 Alternative Materials Investigation

The prototype and initial production Pelamis devices use steel for the main structure as it allows manufacture using industry-standard plant and relatively straightforward structural analysis. These factors are important at this stage of development where theoretical concepts and novel systems are being proven and adapted. However, more specialised materials and manufacturing methods are being explored for future generations of machine. This includes the replacement of the main steel tubes (shell filler sections, Figure 5) with either concrete or glass-reinforced plastic (GRP) with the more complex fabrications, e.g., nose cone remaining in steel. For the purpose of illustrating the impact of these changes, it is assumed that all other elements of the machine life cycle remain unchanged with the exception of disposal which will be affected by the recyclability of the alternative materials.

Although more recent designs for the concrete tubes exist, the design used here [31] retains the existing dimensions to allow direct comparison. Each 125mm thick, 1% steel-reinforced, concrete tube would be post-tensioned by 8 steel tendons (cross-sectional area of 2359 mm^2). Replacement of the shell filler sections requires almost 310 t of reinforced concrete while the remaining steel fabrications and the post-tensioning tendons weigh 124 t. The large mass of the concrete sections allows the sand ballast to be reduced significantly.

The GRP main tube section design, also based on [31] is a hollow core sandwich construction with 6 mm thick inner and outer skins and a 50mm hollow core stiffened by 4mm thick corrugated GRP sheet. Replacement of the shell filler sections requires 33 t of GRP, steel sections of 110 t as well as significant extra ballast to compensate for the relatively small mass of GRP.

Figure 12 shows how changes in the tube materials affects the CO_2 emissions associated with manufacture as well as the recycling. In manufacturing terms, the very low embodied energy and carbon of 1% steel-reinforced concrete (1.81 MJ/kg and 0.222 kgCO_2/kg, respectively) makes concrete much less intensive than steel plate construction (Table 1). Although GRP is more intensive than steel, the relatively low mass also provides a net reduction in energy and carbon terms. Although less recyclable than the all-steel construction, the steel content of the post-tensioning tendons mean that the concrete option provides more recycling credit than GRP. This assumes that the steel can be safely and economically separated from the concrete. Relative to an all-steel construction, the use of GRP for the main tube material results in an 11% reduction in energy intensity to 262.7 kJ/kWh and a two month improvement in energy payback. The carbon intensity is reduced by 6% to 21.6 gCO_2/kWh with carbon payback falling to 12 months. The use of concrete reduces energy intensity by 25% to 219.3 kJ/kWh with energy payback falling by 5 months to 15 months. Carbon intensity falls by 19% to 18.4 gCO_2/kWh and payback is reduced to 10 months. As such, the environmental impact of the Pelamis can be improved by substituting GRP or, better still, concrete for steel in the construction of the main tube sections. These savings are also mirrored by significant reductions in capital cost using GRP and, particularly, concrete construction.

4.4 Sensitivity Analysis

There are several potential sources of uncertainty in this study arising from non-availability of data. These include the omission of energy or CO_2 emissions associated with certain materials or processes or the assumptions made in response. These exclusions and assumptions have been justified earlier and are not expected to have an impact on the overall results of the analysis or the conclusions drawn. However, there were several factors that could materially affect the results which include: production, design life, steel recycling rate and the embodied energy and CO_2 of the materials and manufacturing processes. The sensitivity of the environmental performance of the Pelamis to these was examined.

The assumed electrical energy produced by the Pelamis (2.97 GWh/year) has a major impact on intensity and payback times as these vary by the same amount. A 10% reduction in production raises carbon intensity to 25.1 gCO_2/kWh and energy intensity to 323 kJ/kWh; energy and carbon paybacks are, respectively, lifted by two and one month. Relative changes in design life have a similar impact to production changes. The recycling rate for steel was conservatively assumed to be 90%. Varying the rate by ten percentage points alters the performance indicators by around 8. Lowering the recycling rate to 80% raises carbon intensity to 24.8 gCO_2/kWh, energy intensity to 317 kJ/kWh and carbon and energy paybacks by one month.

The materials data from the Inventory of Carbon and Energy [20] used in this study are subject to uncertainty; typically ranges for energy values of ±30% are presented. Extreme scenarios for high and low materials values were examined with the same ranges assumed to apply to carbon intensity. Application of the high materials values raised respective energy and carbon paybacks to 27 and 18 months (intensities raised to 400 kJ/kWh and 31.6 gCO_2/kWh). The low materials values gave an energy payback of 12 months and an intensity of 187 kJ/kWh with a carbon intensity of 14.2 gCO_2/kWh and payback of 8 months. Typically, the payback and intensities change by around 13% for every 10% change in material value. Further work on the variance of material embodied energy and CO_2 would help greatly in reducing the uncertainty in device environmental performance.

Other notable uncertainties in the materials and manufacturing stage were the use of cost-based estimates for the electrical and electronics systems and assumptions over manufacturing processes. The impact of the cost-based estimators for the electrical and electronics systems was assessed by doubling the estimate of embodied energy and CO_2 for these systems. This resulted in an increase in energy and carbon intensity of less than 3% with paybacks raised by less than a month. Similarly, doubling figures for all manufacturing operations (e.g., sand-blasting) raised energy and carbon intensities by less than 4% to 304 kJ/kWh and 23.6 gCO_2/kWh, respectively. Both show that any error in the cost-based approach or the data for manufacturing operations falls well within acceptable tolerances.

Overall, even under the most adverse scenario considered in the sensitivity study the environmental performance of the Pelamis remains very good and comparable with large wind turbines.

4.5 Improvements and Further Work

The use of materials and shipping are the primary contributors to the Pelamis' environmental impact; addressing these areas would appear to provide the most effective means of improvement. The embodied energy and carbon of the stock materials contribute just over half of the life cycle totals. Increased structural efficiency will help achieve minimisation of material use. As outlined in Section 4.3, the use of concrete or GRP for the main tube sections can provide significant savings in cost, energy and CO_2. Shipping contributes over 40% of the embodied energy and carbon for the Pelamis. This impact could be significantly reduced by utilising newer and more fuel-efficient vessels in sea-borne operations. Should experience dictate that it is possible to reduce the shipping associated with maintenance this too would significantly improve the environmental impact.

The results of this study may best be improved by conducting a full mass and materials classification for the hydraulics and non-electronic electrical systems components. Doing so would allow for both a meaningful materials breakdown to be presented and would increase the potential for recycling.

5 CONCLUSIONS

The vast wave energy resource is beginning to be exploited in the UK in light of climate change and security of supply concerns. The first wave energy converter to be deployed commercially is the Pelamis, developed by Ocean Power Delivery. Success of the first wave farm could eventually lead to the manufacture of large numbers of these devices. As such, it is important that the environmental impact of the Pelamis and, in particular, its life cycle energy and CO_2 performance is evaluated.

This paper presents a detailed analysis of the life cycle energy use and CO_2 emissions associated with the first generation of Pelamis converters. It shows that at 293 kJ/Wh and 22.8 gCO_2/kWh, the respective energy and carbon intensities are broadly comparable with large wind turbines and very low relative to fossil-fuelled generation. The energy payback period is approximately 20 months and the CO_2 payback is around 13 months.

The results are based on a high rate of recycling of the major structural steel components being achieved. As with wind turbines, the materials and manufacturing processes for the Pelamis are identified as the primary contributors to total embodied energy (52%) and carbon (53%). Interestingly, shipping accounts for 42% of the embodied energy and CO_2. Improvements in the environmental impact of the Pelamis can be achieved by increased structural efficiency or replacement of the steel tube sections with alternative materials: reinforced concrete offers reductions in energy and carbon intensity of 25% and 20%, respectively, with smaller savings with glass reinforced plastic. The use of newer, more fuel-efficient sea vessels in shipping operations would also offer significant environmental performance benefits.

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Figures

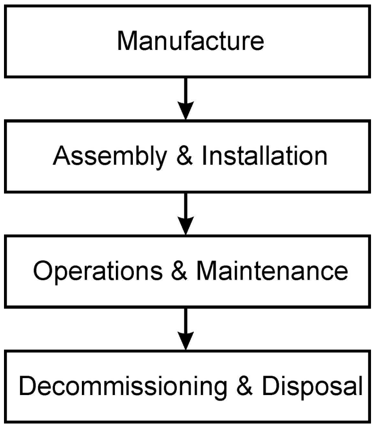

Figure 1 – Product Life Cycle of WEC

Figure 2 – Pelamis wave energy converter

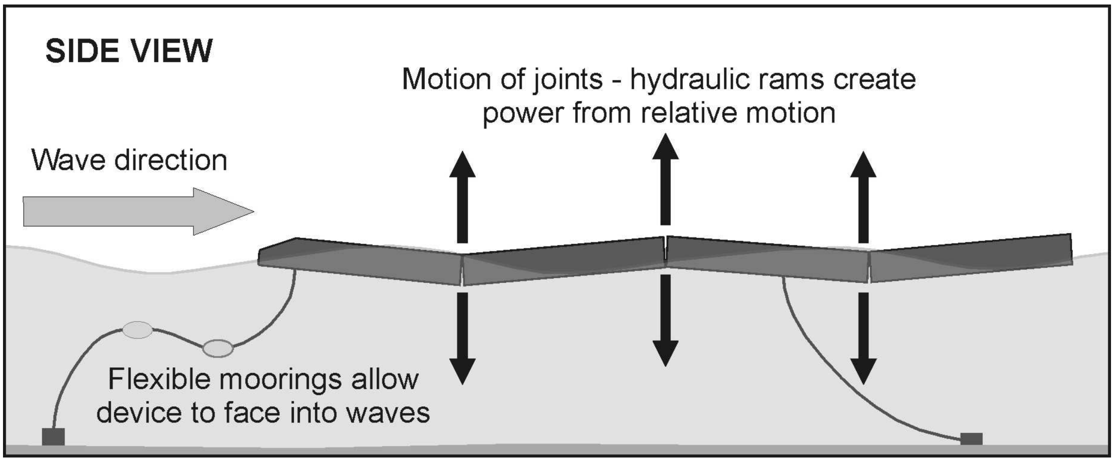

Figure 3 – Side view of the Pelamis, adapted from [16]

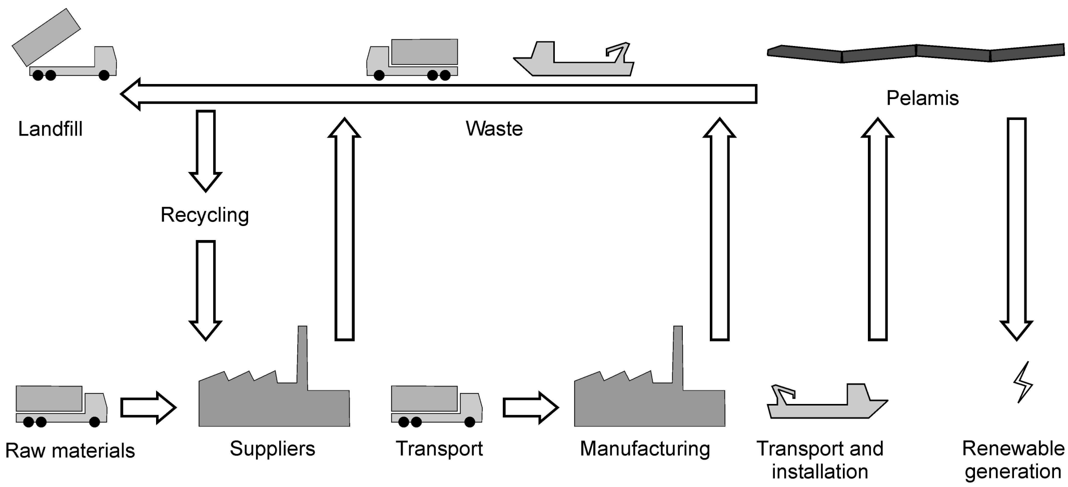

Figure 4 – Detailed Product Life Cycle, after [7]-[8]

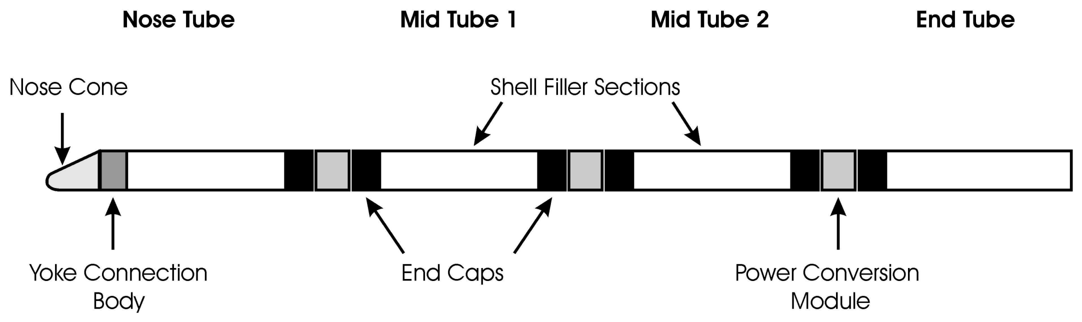

Figure 5 – Structural elements of the Pelamis

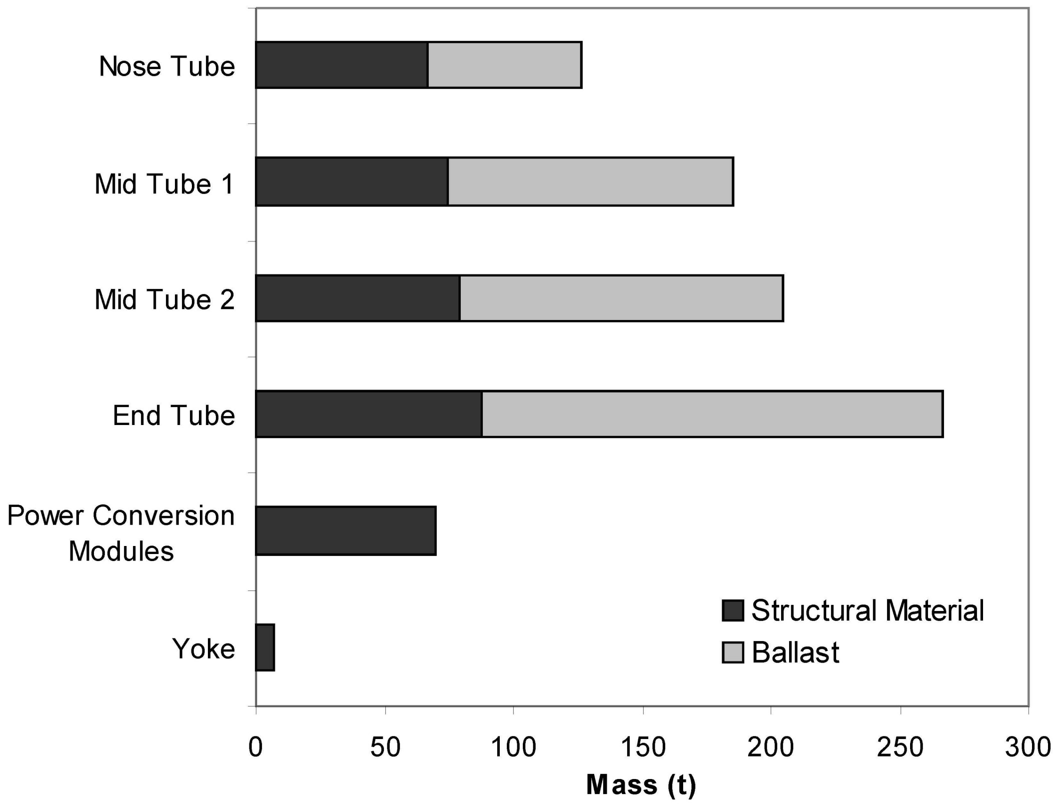

Figure 6 – Mass of Structural Elements

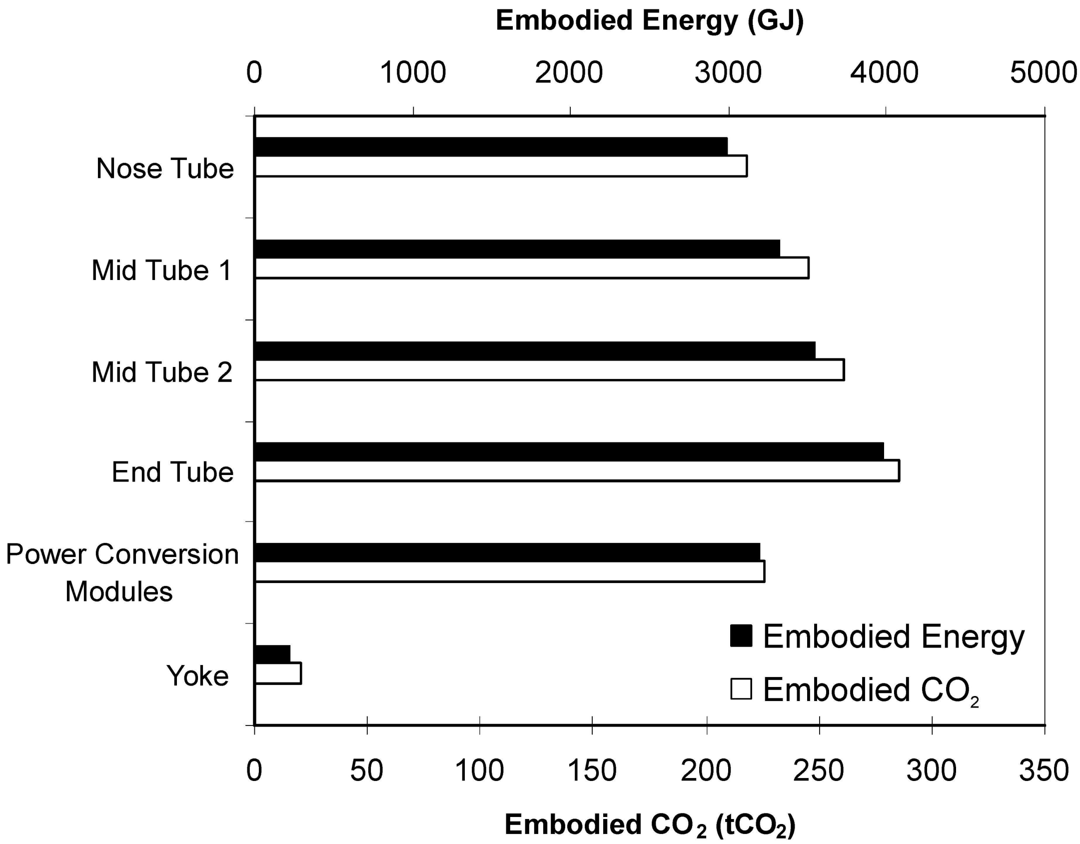

Figure 7 – Structural embodied energy and CO_2

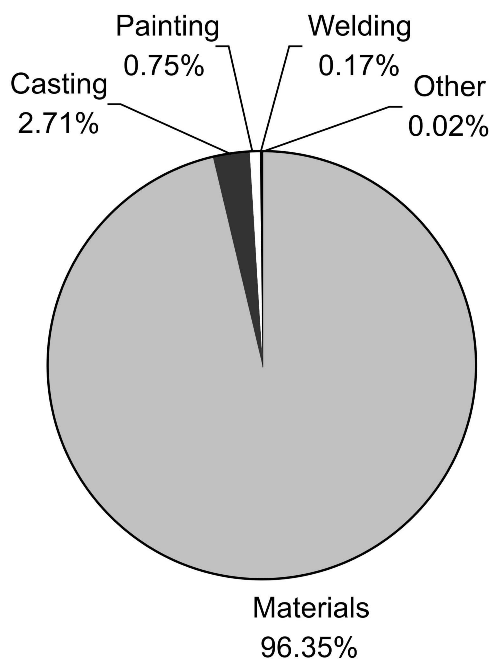

Figure 8 – Breakdown of embodied energy in structural manufacture

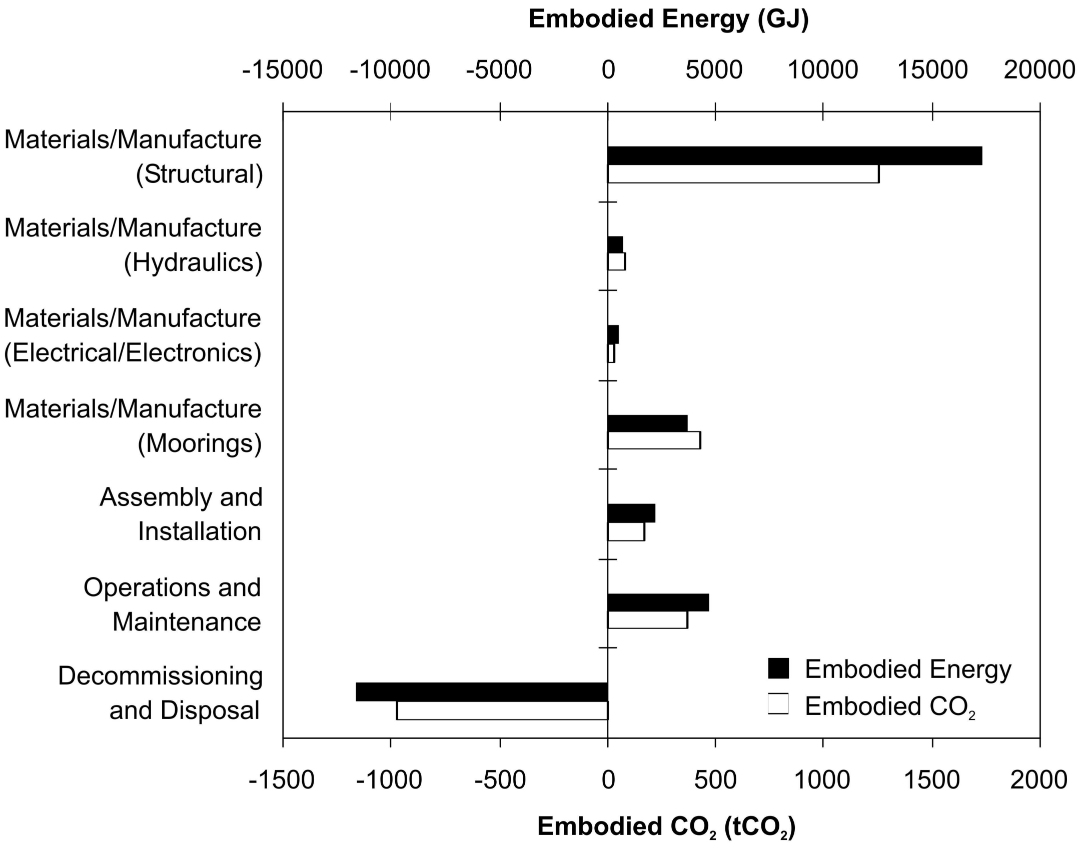

Figure 9 – Embodied energy by life cycle stage

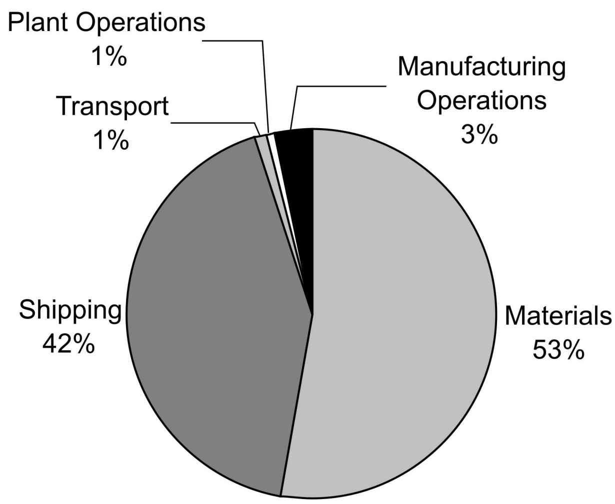

Figure 10 – Contributions to embodied CO_2

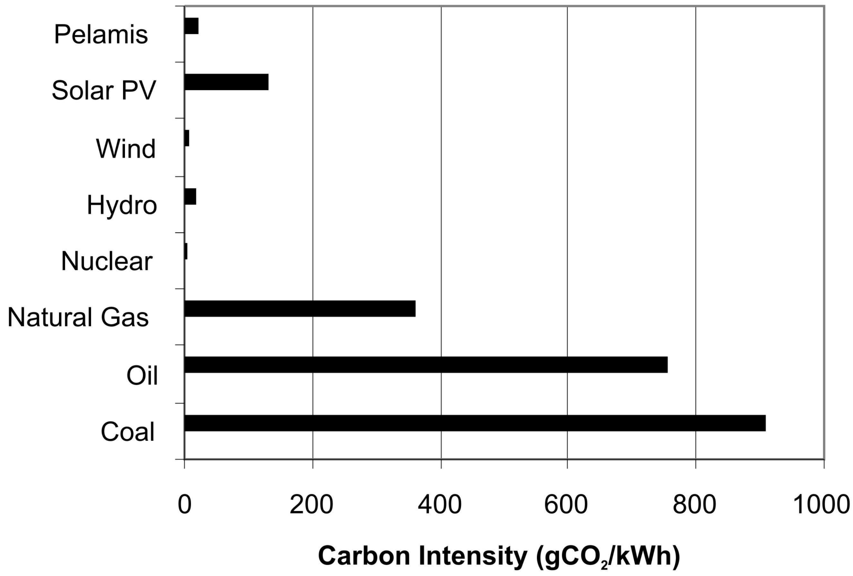

Figure 11 – Pelamis carbon intensity relative to other generation technologies, after [30]

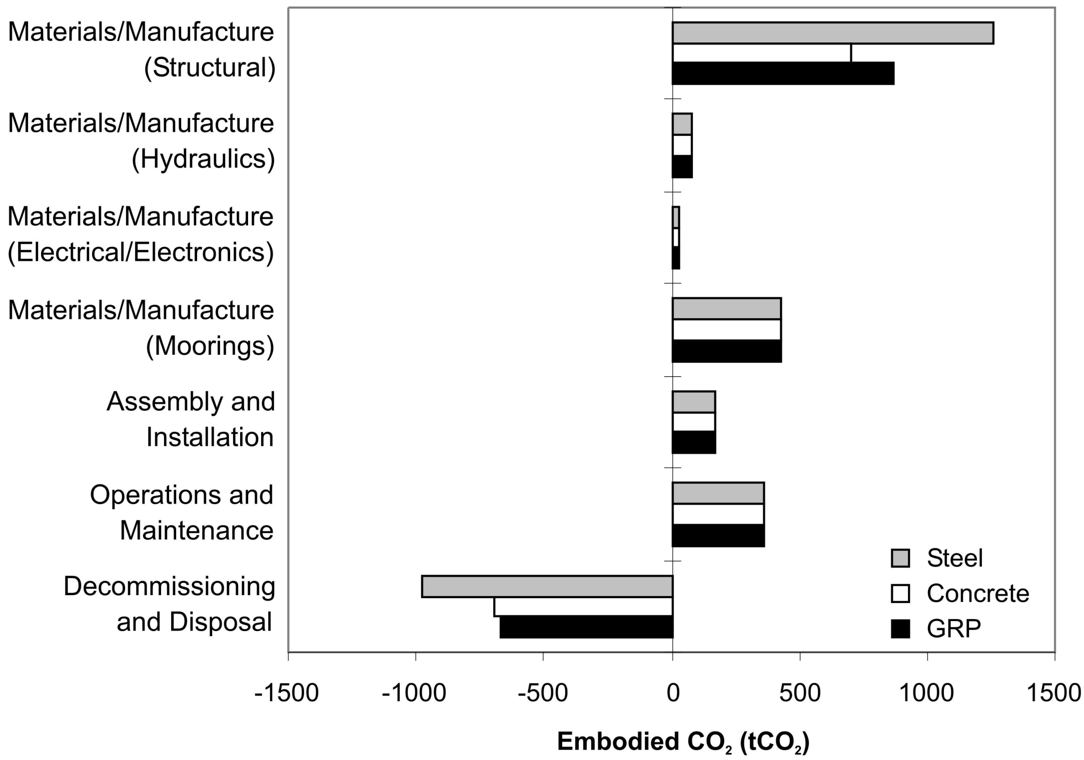

Figure 12 – Comparison of embodied CO_2 with alternative materials